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Fatigue behavior of ferroelectric ceramics under mechanically–electrically coupled cyclic loads

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Abstract

The fatigue behavior of commercial ferroelectric ceramics PZT-5 was studied by carrying out four-point bending experiments for the poled and unpoled samples. Two types of mechanical loads (constant and cyclic) coupled with a cyclic electrical field were applied. It was observed that under the same cyclic electrical field the fatigue life of the PZT ceramics significantly reduced as the applied mechanical loads (either constant or cyclic) became larger. When coupled with the same electric field, the application of constant forces lowered the fatigue life of the poled samples more significantly than that of the unpoled samples, while the application of mechanically cyclic load remarkably decreased the fatigue life of the unpoled samples.

Keywords: Ferroelectric ceramics; Mechanically–electrically coupled load; Fracture; Fatigue life; Critical fracture force

1. Introduction

Ferroelectric ceramics has a broad range of applications due to its strong anomalies in physical properties, such as dielectric coefficient, electric-optical coefficients, piezoelectric coefficients, elastic coefficient [1–3]. Ferroelectric transducers are easier to be damaged because they are always used under high electrical cyclic field coupled with a mechanical loading condition. Fatigue caused by the mechanically–electrically coupled loading appears to be most fatal. When a ferroelectric transducer or memory unit is damaged, it cannot transform energy effectively and should be replaced. Since it is hard to determine when the ferroelectric transducer is damaged, it is extremely important to understand the fatigue response of ferroelectric material under a mechanically–electrically coupled loading condition. There are considerable reports on experimental studies of fatigue induced either by an electrical or a mechanical load alone [4–11]. However, fatigue due to a mechanically–electrically coupled load has not yet been investigated so far.

This work was conducted to experimentally observe the fatigue life of ferroelectrics under mechanically–electrically coupled loads. Four-point bending experiments on commercial ferroelectric ceramics PZT-5 ($Pb(Zr_{0.54}Ti_{0.46})O_3$) were performed under different levels of mechanically-electrically coupled loads for the poled and unpoled samples. Two types of mechanical loads, either being constant or being cyclic, coupled with a cyclic electrical field were applied to the samples for a comparison. The magnitudes of the critical fracture force were also experimentally determined for the poled and unpoled samples, respectively, under different loads.

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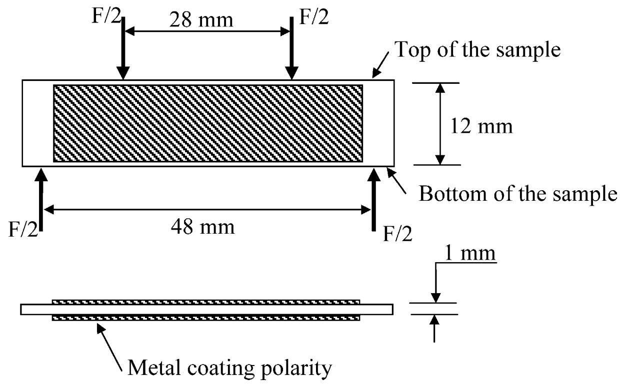

Fig. 1. Sketch of samples and loading mode.

2. Experimental

The dimensions of samples used for the four-point bending experiments and the loading mode are shown in Fig. 1. The dimensions of sample were determined according to the following two requirements: (1) the electrical field in the samples is strong enough so that the domain switching process will be able to be saturated under the applied electrical load; and (2) the sample should be able to sustain a large enough mechanical force. The first requirement implies that the strength of the applied electrical field should be as high as hundreds thousands voltages per meter. The second requirement means that the higher the sample is, the larger is the applied mechanical force that the sample may sustain.

Due to the restrain of the instruments, the thickness of the samples was chosen to be 1 mm so that an applied electrical load with a magnitude smaller than 1000 V may satisfy the first requirement. To satisfy the second requirement, the height of the samples was chosen to be 12 mm. A concern about the flexures of samples under the mechanical load led us to prepare samples carefully. In order to prevent the flexure during the experiments, an effort was made to ensure that the bottom and top surfaces of the samples were parallel to each other and were perpendicular to the lateral surfaces. During the experiments, no flexure was observed.

Clearly, the material in the pure bending portion of the samples experiences a compression deformation or a compression–compression fatigue deformation if it is located above the neutral layer of the sample, and undergoes a tension deformation or tension–tension fatigue deformation if it is located below the neutral layer of the sample. In addition, the direction of the applied electrical field is perpendicular to the direction of the non-zero principal stress as illustrated in Fig. 2.

Both poled and unpoled PZT-5 samples were tested in this work. The material was sintered at 1225 °C for 45 min. The grain size of the material is about 3 μm. The Curie point for the material is 325°C. To ensure a good

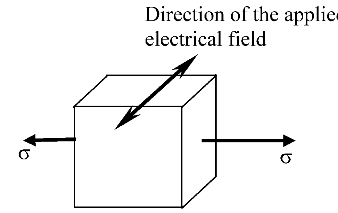

Fig. 2. Sketch of the mechanically–electrically coupled loading condition for an element taken from the pure bending portion of samples that is below the neutral layer.

integrity of the electrode during the experiments, a silver electrode was sintered on the lateral surfaces of the samples. The polarization of the material was done by applying a direct electric field of the strength 3400 kV m^{-1} on the material with the temperature being kept at 100 °C.

For the poled samples, the direction of the applied electricl field is chosen to be parallel to the poling direction. The fatigue lives of the poled and unpoled samples were observed under two types of mechanically–electrically coupled loading modes. In both modes, a cyclic electrical field $E = 862\ \mathrm{Sin}(100\pi t)$ kV m^{-1} was applied. The magnitude of the electric field was chosen so that the domain switching process would be saturated. However, in one of the modes, the applied external force was kept constant during the test, and in the other mode, the applied external force was also cyclic with $F = \bar{F} + F_a\ \mathrm{Sin}(2\pi ft)$. Here $\bar{F}$ is the mean value of the applied force, F_a is the amplitude, f is the frequency generated automatically by the high frequence fatigue testing system. By taking $\bar{F} > 0$ and $F_a = (0.9/1.1)\overline{F}$, the applied external cyclic force F is guaranteed to be greater than zero. The maximum principal stress, therefore, may be expressed as $\sigma_{max} = \bar{\sigma}_{max} + \sigma_{a\ max}\ \mathrm{Sin}(2\pi ft)$, where $\bar{\sigma}_{max}$is the avarege maximum stress within the sample induced by $\bar{F}$. Detailed testing information is summarized in the Table 1.

3. Results and discussion

3.1. Under a mechanically constant force coupled with a cyclic electric field

It was found that without a coupling electric field, the samples would not fracture until the applied force reached 200 N. However, when coupled with an electric field, the samples would break under the applied force that was far below 200 N. It was also noted that the maximum bending stress σ_{max} for both poled and unpoled samples varied with the changes of the electric fatigue life. When the total number of electric cycles endured by the samples was low, the unpoled samples could sustain a greater maximum bending stress than that the poled samples could. However, as the total

Table 1
Testing conditions for four-point bending measurements

Load mode	Mechanical load			Electrical field	
	$\bar{F}$ (N)	F_a (N)	f (Hz)	E_{max} (kV m^{-1})	f (Hz)
(1) Constant forces	20, 26.7, 40, 46.7, 60 and 80 N			862	50
(2) Cyclic forces	14.7	12	71.5	862	50
	22.0	18	74.0		
	14.7	12	72.0		
	22.0	18	74.5		

number of electric cycles endured by the samples increased, the maximum bending stresses at which both samples could sustain decreased, but approached to about the same magnitude after the total number of the electric cycles exceeded 1.08×10^6. For a standard consideration, we call the minimum constant force applied to a sample which would cause a fracture in the sample only after the total number of the electric cycles is greater than 1.08×10^6 the critical fracture force (F_c). The values of F_c for the poled and unpoled PZT-5 samples were experimentally determined to be about 40 and 33.3 N, respectively.

The maximum bending stresses corresponding to mechanically constant external forces in both poled and unpoled samples were compared in Fig. 3 as a function of electric fatigue life (in terms of total numbers of electric cycles). Apparently, the fatigue life of the poled samples was shorter than that of the unpoled samples under the same mechanically–electrically coupled load. For both types of smaples, it was shown that the higher the applied external force, the lower the fatigue life.

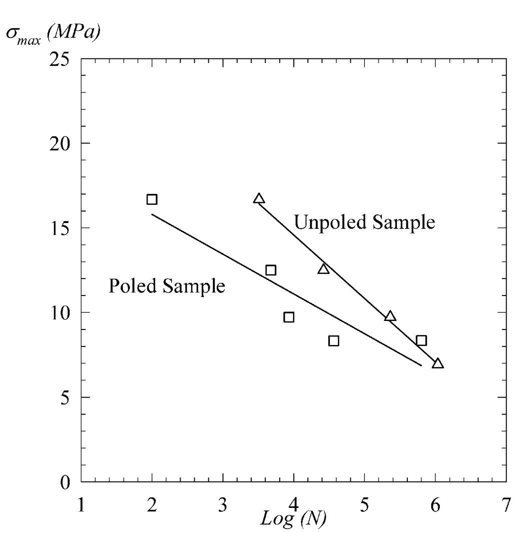

Fig. 3. Effects of the applied constant forces on the electric fatigue life of poled and unpoled samples. The magnitude and frequency of the applied alternative electric field are 862 kV m^{-1} and 50 Hz, respectively.

The change of the ratio between the remnant polarization (P_r) and the initial remnant polarization (P_r^0) is normally employed to describe the electric fatigue life of PZT-5. In order to investigate the effect of the coupled applied forces on the ratio during an electric fatigue test, the ratio P_r/P_r^0 was plotted as a function of the total number of electric cycles in Fig. 4 for both poled and unpoled samples when the coupled forces were 20 and 26.67 N, respectively. It is evident that the electric fatigue life of the unpoled samples dropped more rapidly than that of the poled samples did. This may be attributed to a more significant increase of microcracks in the unpoled samples as the total number of electric cycles increases. As the number of microcracks increases, the overturning of electric domains became less easily, which results in shrinkage of the hysteresis loop.

3.2. Under a mechanically cyclic load coupled with a cyclic electric field

The average maximum tensile stress ($\bar{\sigma}_{max}$) associated with the applied average force $\bar{F}$ for both poled and

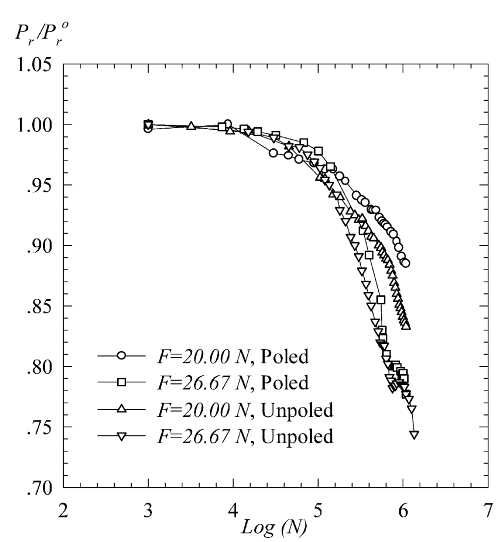

Fig. 4. Variations of the polarization ratio P_r/P_r^0 of poled and unpoled samples with the number of electric cycles for different applied forces. The magnitude and frequency of the applied alternative electric field are 862 kV m^{-1} and 50 Hz, respectively.

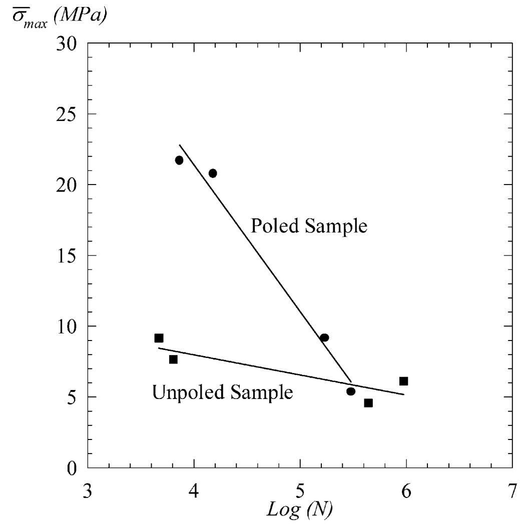

Fig. 5. Effects of the applied cyclic forces on the fatigue life of poled and unpoled samples. The applied electric field is $E = 862\ \mathrm{Sin}(100\pi t)$ kV m^{-1}, and the applied cyclic forces are: $F = \bar{F} + F_a\ \mathrm{Sin}(2\pi f t)$ N, where f ranges between 71.4 and 74.6 Hz, $\bar{F}$ takes 20 and 22.67 N, $F_a = (0.9/1.1)\bar{F}$. $\bar{\sigma}_{max}$ is the maximum tensile stress within the sample induced by $\bar{F}$.

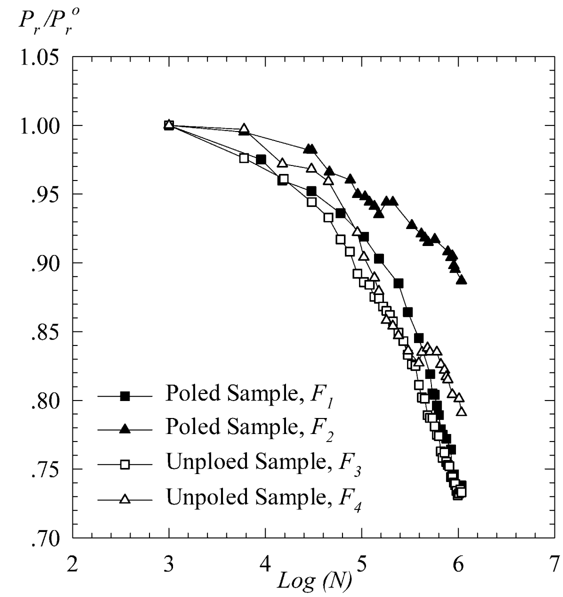

Fig. 6. Variations of the polarization ratio P_r/P_r^0 of poled and unpoled samples with the number of electric cycles for different applied cyclic forces: $F_1 = 14.667 + 12\ \mathrm{Sin}(143\pi t)$ N, $F_2 = 22 + 18\ \mathrm{Sin}(148\pi t)$ N, $F_3 = 14.667 + 12\ \mathrm{Sin}(144\pi t)$ N, $F_4 = 22 + 18\ \mathrm{Sin}(149\pi t)$ N. The applied alternative electric field is $E = 862\ \mathrm{Sin}(100\pi t)$ kV m^{-1}.

unpoled samples are plotted in Fig. 5 as a function of the electric fatigue life (the total number of electric cycles). The poled samples showed faster decrease in $\bar{\sigma}_{max}$, while the unpoled samples responded to $\bar{\sigma}_{max}$ less sensitively, which are notably different from what were observed under a mechanically constant force coupled with a cyclic electric field as compared with Fig. 3. This may suggest that, when coupled with a cyclic electric field, the applied mechanically cyclic load seems to have more complex influences in the degradation of PZT materials. Ferroelectric ceramics generally consists of many domains. Each domain has its own poling direction. The poling directions of the poled samples in each domain are more uniform than those of the unpoled samples, and may be more remarkably changed by the applied mechanically–electrically coupled cyclic load, thus the electric fatigue life of the poled samples might be reduced more significantly.

Similarly, the minimum average force $\bar{F}$ applied on samples which causes a fracture in samples under a mechanically cyclic force coupled with a cyclic electrical field is defined as the average critical fracture force ($\bar{F}_c$). The values $\bar{F}_c$ for the poled samples and unpoled samples were then measured to be 27 and 22 N, respectively, which are significantly lower than those measured under a constant force coupled with a cyclic electric field as aforementioned.

The relationship between the ratio P_r/P_r^0 and the fatigue life of the poled and unpoled samples are shown in Fig. 6. Under the same mechanically cyclic load, the electric fatigue life of the unpoled samples reduced more rapidly than that of the poled samples did, in particular under a high number of cycles. The higher the applied cyclic force, the lower the electric fatigue life. This is consistent with the fatigue behavior observed when the smaples were under a mechanically constant force coupled with a cyclic electric field as shown in Fig. 4.

4. Summary and conclusion

The fatigue behavior of commercial ferroelectric ceramics PZT-5 ($Pb(Zr_{0.54}Ti_{0.46})O_3$) under mechanically–electrically coupled loads were investigated by performing four-point bending experiments for the poled and unpoled samples. The preliminary results revealed that under the same cyclic electrical field, no matter whether the coupled mechanical load was constant or cyclic, the higher the coupled mechanical load, the lower the fatigue life of samples for both poled and unpoled samples. The maximum tensile stress of the poled samples dropped more rapidly as the total number of electric cycles increased than that of the unpoled samples did under mechanically constant forces coupled with a cyclic electric field, while the average maximum tensile stress of the unpoled samples reduced more significantly under a mechanically cyclic force coupled with a cyclic electric field.

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